Automated Efficiency Meter

Technical Report

Group SD1023

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Table of Contents

Background

Manually measuring the efficiency of voltage regulators across their entire operating range is a tedious and time consuming process. Measuring the efficiency of a regulator with two input voltages and two output voltages manually requires eight multimeters and hundreds of measurements. To measure across the entire operating range could occupy an entire eight hour work day. Currently our client, Packet Digital, must take their efficiency measurements manually. Our goal is to automate this entire process and reduce the time required to a couple of minutes. The difference between manual measurements and our system can be seen in the following two figures. With our setup all you have to do is plug in a few wires and set a few setting in software and that is it.

Figure 1: Manual Setup

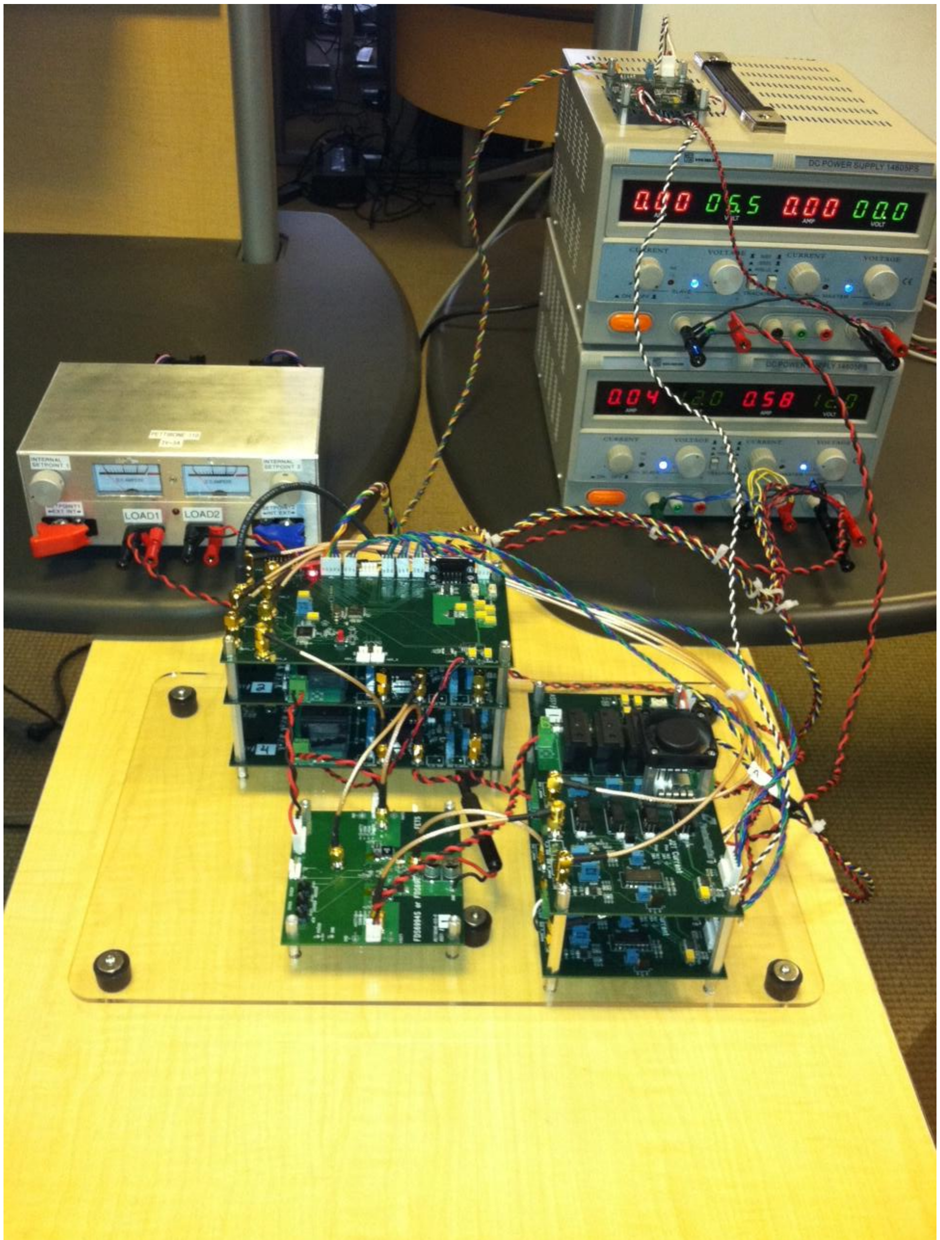


Figure 2: Complete Design

Requirements

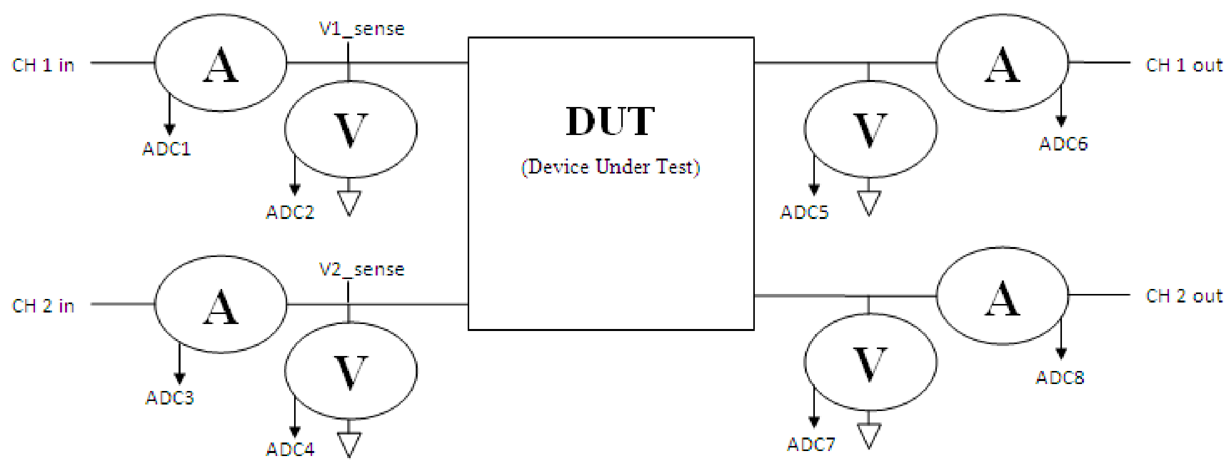
- Automate efficiency measurements on single and dual channel devices
    - Test parameters such as voltage input and current output levels should be able to be set by the user in software
    - We will create predefined tests that give efficiency measurements over a wide range of input voltages and output currents
    - Output measurements should be saved to a computer and automatically plotted on a graph
    - The graphs that will be plotted are efficiency vs. load current at the user defined input voltages

- On the input and output sides the device should be capable of measuring current and voltage on four channels
    - All channels must be capable of measuring 0 to 30V with 10uV precision
    - All channels must be capable of measuring 1uA to 10A with 1uA precision
    - Input voltage should provide feedback to ensure proper voltage at the device under test
    - All eight measurements must be taken simultaneously at a rate of no less than 10kHz
    - Power will be measured instantaneously and calculated in software as an average
- All calibrations should be done in hardware when possible
- Power supply can be built from scratch or can be assembled from off the shelf modules or components but it must be able to deliver 0 to 30V to the input for any given current being drawn by the output (1uA to 10A)

Constraints

- Efficiency measurement should be accurate to within 0.05% of the actual value
- Device must be capable of handling 0 to 30 V and 1uA to 10A
- Unit should be modular so that all of the sensing boards can be interchanged
- Budget of $1500

Block Diagrams



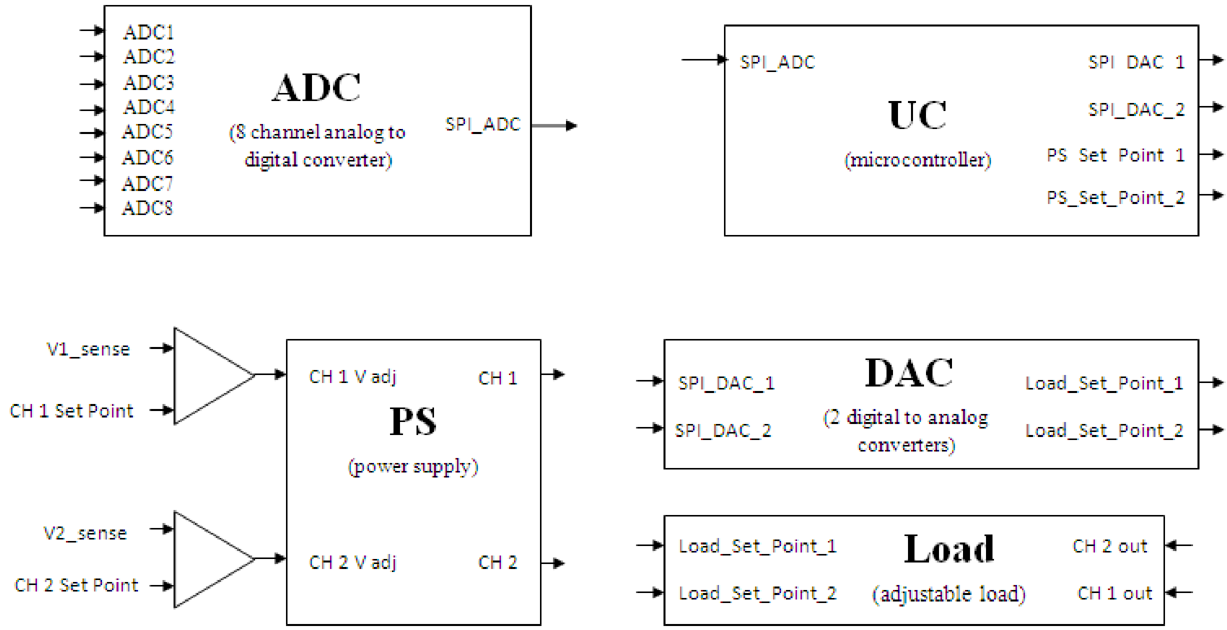


Figure 3: Block Diagrams

Schematics and Descriptions

Our project is split up into several parts. We designed three different circuit boards for this project. The first board that we designed was the power measuring board. Because we are measuring power on four different lines across such large dynamic ranges we decided to use a separate circuit board for each power measurement, therefore each board measures one voltage and one current.

Current Measurement

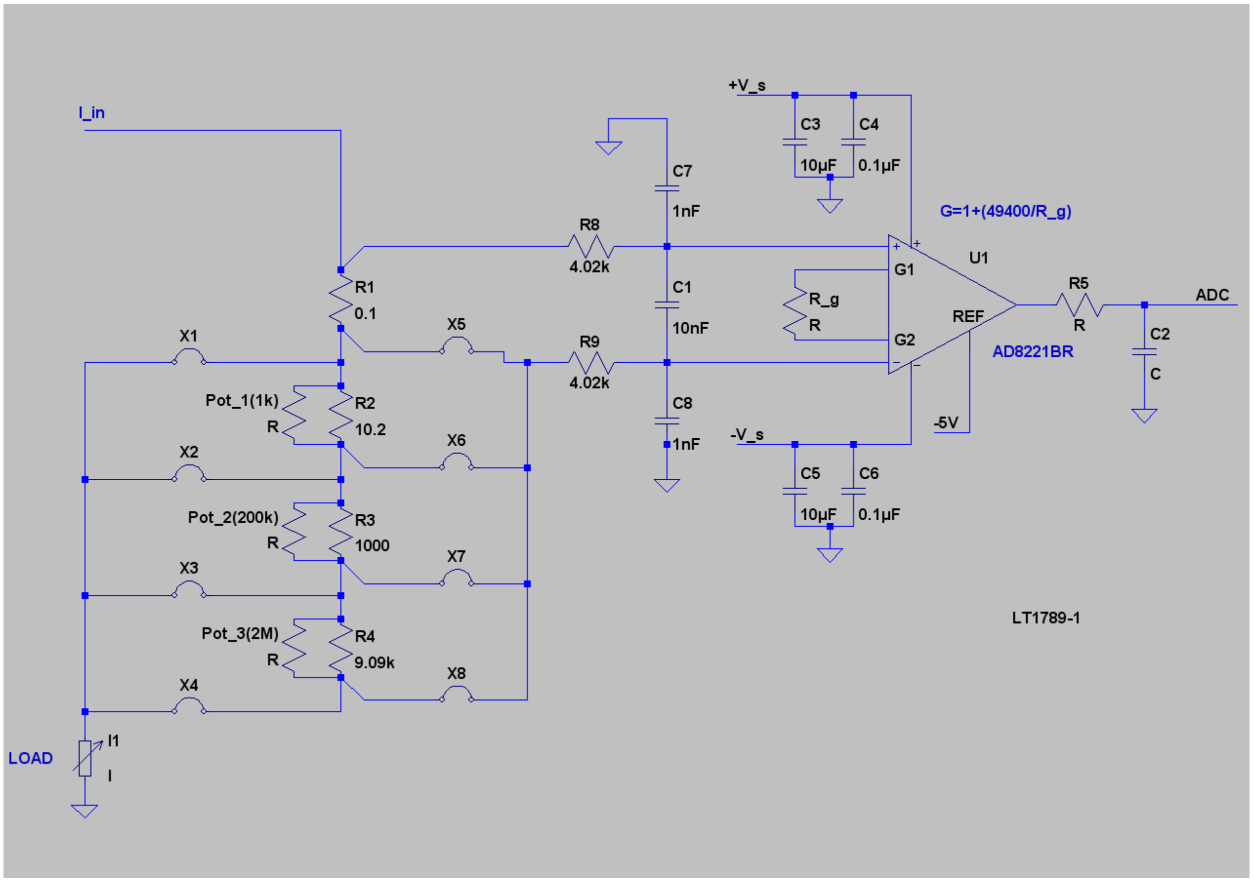


Figure 4: Simplified Current Measurement Circuit

Theory of Operation

This circuit uses the high side current sensing technique to measure a voltage drop across a sense resistor. The voltage across the sense resistor is then amplified by an instrumentation amplifier and sent to an ADC and then to a microcontroller for further processing. This circuit consists of four different current sensing ranges to cover the entire required dynamic range. Current sensing resistors R1 through R4 are switched into the circuit appropriately using relays. Care must be taken to start switching the resistors into the circuit starting with R1 so that the circuit is not damaged due to large power drops across the sense resistors. The gain of U1 is approximately five. It is fine tuned by adjusting R_g based on the actual non-ideal resistance of R1 to get an accurate measurement. The Pots on R2, R3, and R4 allow for fine tuning of the additional ranges to get accurate measurements.

The next stage in the circuit makes up the input filtering section. This part of the circuit consists of R8, R9, C1, C7, and C8. These components minimize noise from the power supply and improve common mode rejection (CMR).

The reference pin is tied to -5V so that we get a voltage swing of -5V to 5V out of U1. This is ideal because the input to our chosen ADC (AD7606) will have the same voltage measurement range.

Parts Selection

1. Amplifier

Most of the other part selection in this circuit is dictated by the amplifier. There were several considerations when choosing an amplifier. Since we had such a large dynamic range we considered using a logarithmic amplifier which would allow us to have a larger range of sense voltages across any given sense resistor. This, in theory, would allow us to use fewer overall ranges thus reducing the number of components in the circuit. The main drawback with this method is that by reducing the number of ranges you are increasing the voltage drop across the sense resistors on the high end of the ranges. In the end we found that the linear amp option and the log amp options would have the same amount of ranges assuming a voltage ranges across the sense resistors of 10mV-2V. We were able to find very good precision instrumentation amplifiers with gain non-linearties as low as 10PPM where as the log amps had gain non-linearities of around 1dB making the IA the logical choice.

After doing some research we found that for a low impedance source and for high side sensing there were several characteristics that were important when choosing an instrumentation amplifier, they include: very high CMRR, low input offset voltage, low noise voltage, and low drift. We also want a reference pin to offset the output voltage and adjustable gain. After looking through many amplifiers the best option available seems to be the AD8221BR. This amplifier offers the following capabilities:

AD8221BR

Supply Voltage: ±15V

- Reference Pin
- Adjustable Gain: 1 to 1000
- CMRR: 110dB @G=10
- Input Offset Voltage: 25μV
- Noise Voltage: 8nV
- Drift: 0.3μV/°C
- Supply Range: ±18V
- Gain Non-linearity: Max 10 PPM @ G=10

Resistor R_g will set the gain of the amplifier according to the formula:

$$R_G = \frac{49.4k\Omega}{G-1}$$

If G=5 then we want **R_g = 12350Ω**

2. Sense Resistors

The ideal sense resistor values were chosen based on the amplifier having a gain of 5 and an output voltage range of 10V. The goal was to keep the gain fairly low to allow for wider ranges and at the same time minimizing the required voltage drop across the sense resistors. We assumed a maximum noise of 10mV meaning that the voltage drop across the sense resistor has a range of 10mV to 1.99V. The ideal resistor values can be seen in the table below.

ADC Range	10	Volts
Noise Threshold	0.01	Volts
Low Sense Voltage	0.01	Volts
Gain	5	
Rsense1	0.1	Ohms
Rsense2	9.9	Ohms
Rsense3	990	Ohms
Rsense4	9000	Ohms
Vout = i*RSeries*G		
Current Max	10	A

Rseries	Imax(A)	Imin(A)
0.1	19.980000	0.100000
10	0.199800	0.001000
1000	0.001998	0.000010
10000	0.000200	0.000001

Rseries	Power Loss (W)	Power Loss (W)
0.1	10.000000	0.001000
10	0.399200	0.000010
1000	0.003992	0.000000
10000	0.000399	0.000000

Rseries	Voltage Drop (V)	Voltage Drop (V)
0.1	1.000000	0.010000
10	1.998000	0.010000
1000	1.998000	0.010000
10000	1.998000	0.010000

Because Rsense2, Rsense3, and Rsense4 are not standard resistor sizes and because we are not tuning the gain individually for each range pots are required for ranges 2-4. The gain can be tuned for accuracy according to range 1 then ranges 2-4 will be fine tuned based on this gain. R2, R3, R4 were chosen by finding the next highest common value above the ideal that would never be less than the ideal based on the tolerance of the resistor. In this way a large pot can be put in parallel with the sense resistors to fine tune them, this limits the current through the pots which is desired because pots have a higher temperature coefficient. The parallel resistances of are calculated using the following formula:

$$R_{EQ} = \frac{R_a R_b}{R_a + R_b}$$

The tolerance of R1 is 1% meaning that it will vary by 1mΩ max which will affect the series resistance by less that 0.009% making it negligible to the following calculations. That being said, we get the following necessary potentiometer values.

	Nominal Res. (Ω)	Tolerance	Min. Res. (Ω)	Max Res. (Ω)	Desired // Res. (Ω)(Min)	Pot Res. (Ω)(Max)	Pot Res. (Ω)(Min)
R2	10.2	0.010	10.098000	10.302000	9.9	504.9	253.71
R3	1000	0.005	995.000000	1005.000000	990	197010	66330
R4	9090	0.001	9080.910000	9099.090000	9000	1010112.35	826438.69

Based on the table above we came up with the following resistor choices.

Resistor Value(Ω)	**Mfg. Part #**
0.1	D2TO035CR1000FTE3
10.2	ERJ-14NF10R2U
1000	RR1220P-102-D
9090	RG2012P-9091-B-T5

3. Input and Output Filters

Filtering is also done at the input to the IA using R8, R9, C1, C7, and C8. The values of these components were chosen to reduce the noise from the power supply and improve CMR. The power supply we are using is the HY3003F-3 which had a measured noise of 50mV at 81MHz. Because this frequency is so high we chose reasonable values for cut off frequency based on common component values using the following formulas.

Let: $R8 = R9 = R$

Let: $C7 = C8 = C_C$

Let: $C1 = C_D$

Using the formulas:

$$FilterFreq_{Diff} = \frac{1}{2\pi R(2C_D + C_C)}$$

$$FilterFreq_{CM} = \frac{1}{2\pi RC_C}$$

Where: $C_D \geq 10C_C$

If : $R = 4.02k\Omega$

$C_C = 1nF$

$C_D = 10nF$

Then: $FilterFreq_{Diff} = 1885Hz$

$FilterFreq_{CM} = 39590Hz$

The Output filter is just a simple low pass filter to reduce high frequency noise on the output.

We have a 49.9Ω resistor at the output of the amplifier and we want a cutoff frequency of about 100KHz so we need a capacitor of 0.033µF. This is determined using the following formula:

$$F_C = \frac{1}{2\pi RC}$$

$R = 49.9\Omega$

$$C = 0.033\mu F$$

We chose a 49.9Ω resistor because we are using 50Ω SMA cables on the output to connect to the ADC so we want to match the impedances. From that we calculated the necessary capacitance.

Voltage Measurement

Measuring the voltage is a pretty simple process which can be seen below.

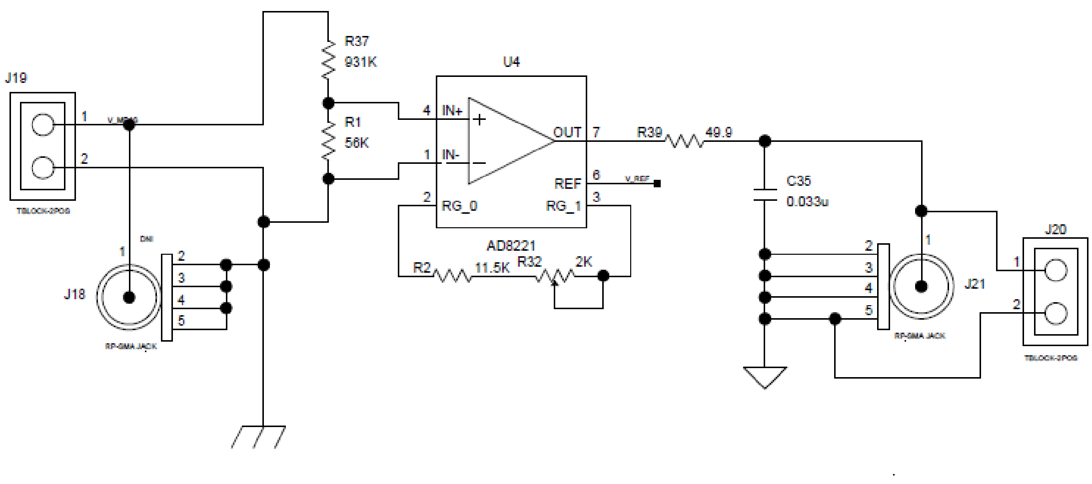


Figure 5: Voltage Measurement Circuit

Theory of Operation

We again use the same IA as we did for the current measuring portion of the circuit. We need to measure voltages from 0V to 30V. To provide a little overhead we did our calculations to allow our circuit to measure up to 35V. Again, we use a gain of five and still keep our output voltage between -5V to 5V.

Using: $V_{out} = V_{in}\left(\frac{R_1}{R_1 + R_{37}}\right)5 - 5$

Then: $0 < V_{in}\left(\frac{R_1}{R_1 + R_{37}}\right)5 < 10$

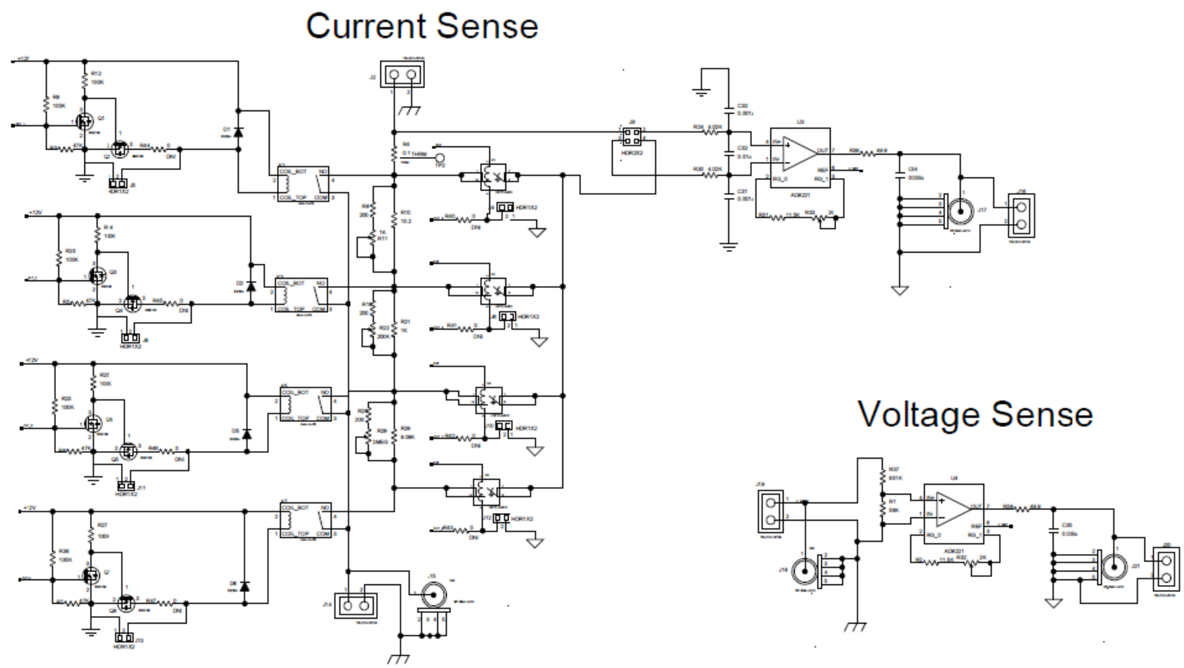
$$\Rightarrow \frac{R_{37}}{R_1} = 16.5$$

We chose R37 and R1 to be sufficiently large so that the current through them is minimal in order to minimize errors in the current measurement. Our largest current sensing resistance will be 10kΩ. So, limiting the current through the voltage sensing resistors to 1% of the total current: $(R_{37} + R_2) = 100(10k\Omega)$

$\Rightarrow\ R_{37} + R_2\ > 1M\Omega$

We again use a potentiometer to adjust the gain to account for tolerances in the resistors.

Overall Power Measurement Schematics



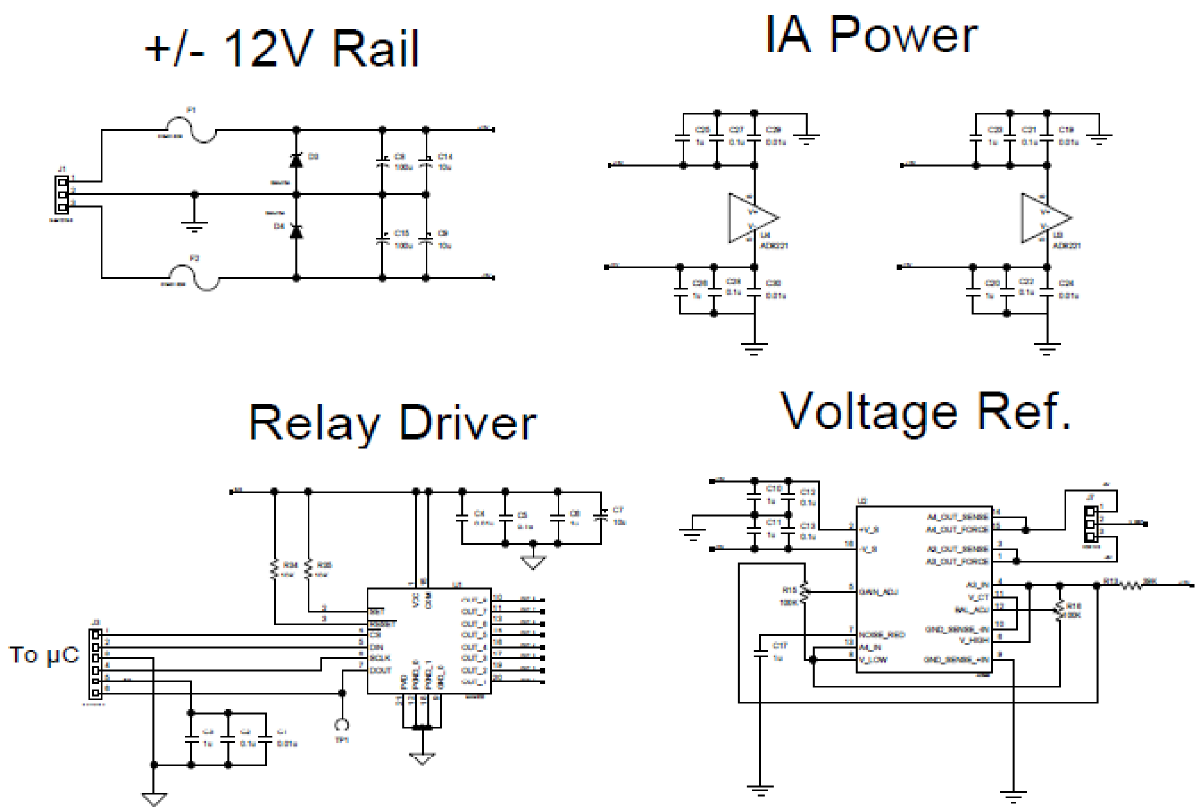


Figure 6: Overall Power Measurement Circuit

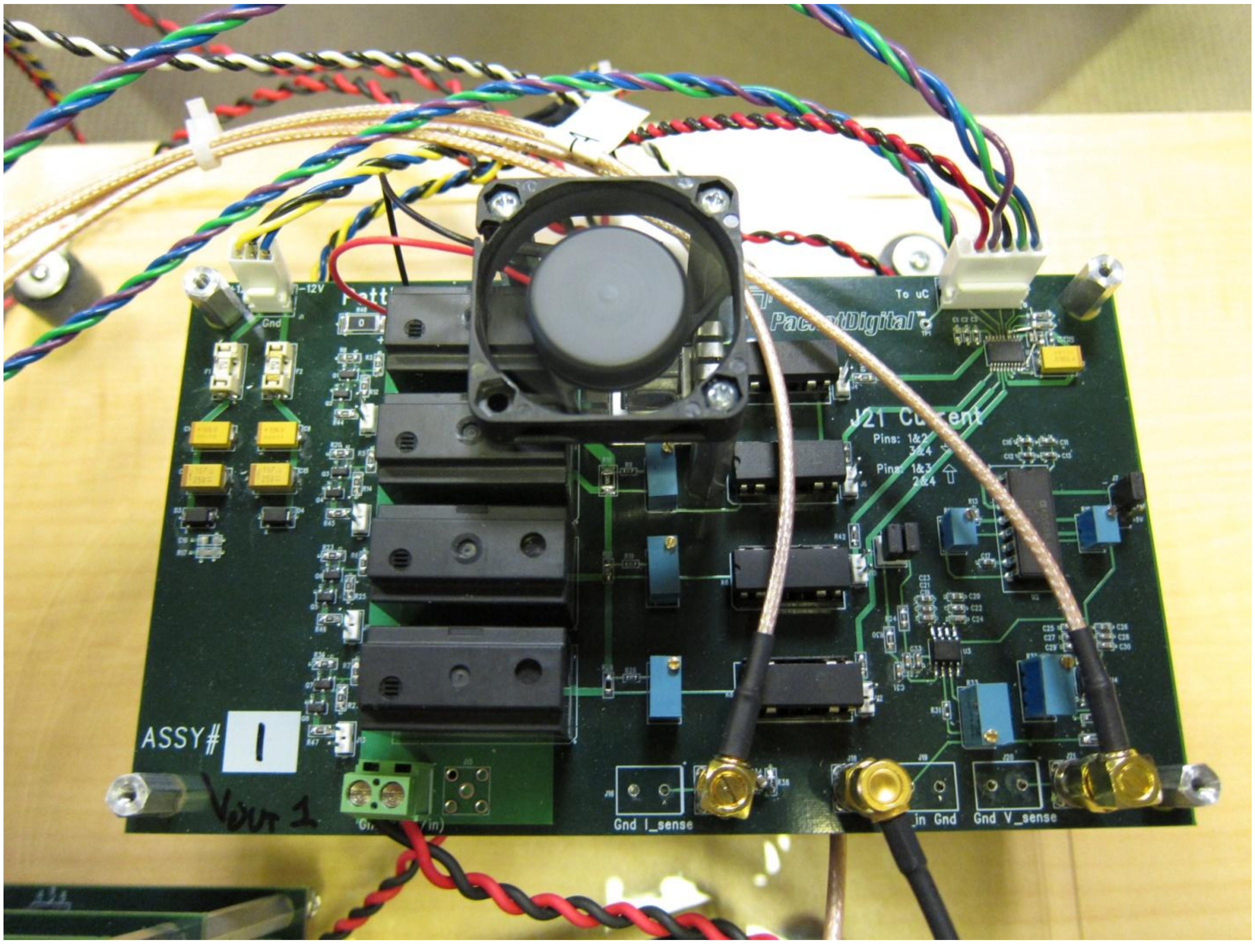


Figure 7: Power Measuring Board

Power Supply Control Circuit

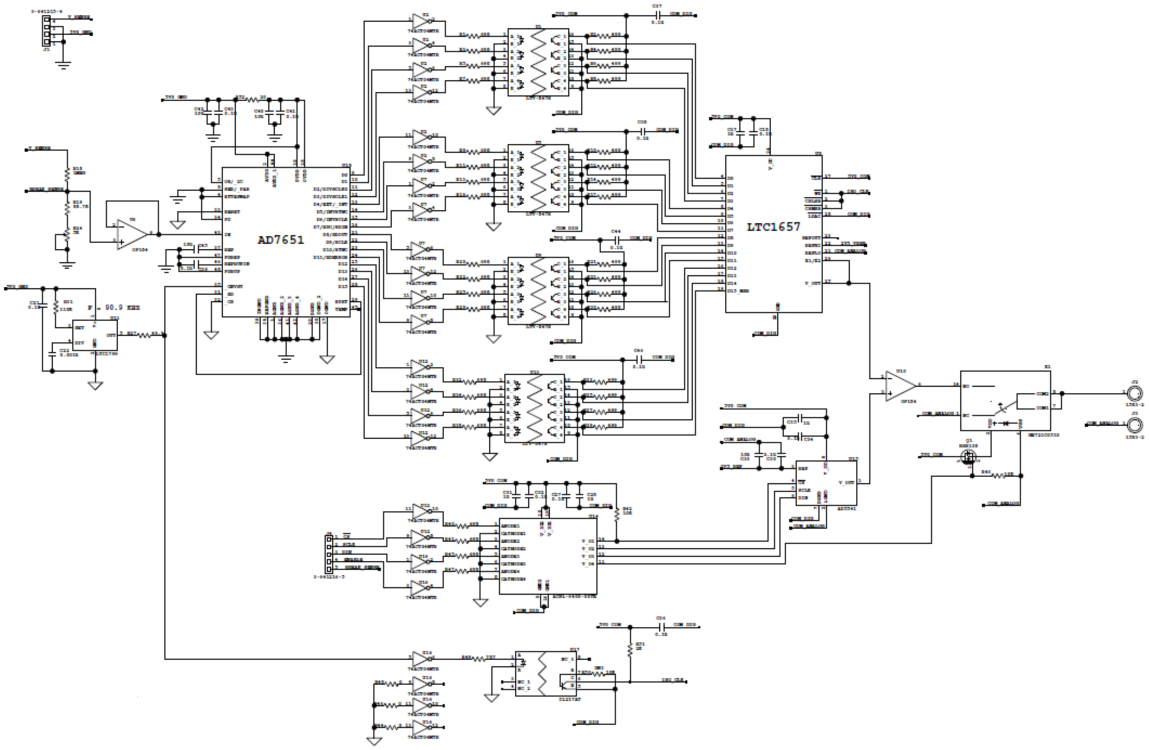


Figure 8: Power Supply Control Circuitry

Figure 9: Power Supply Control Board

Theory of Operation

This circuit controls our power supply. The power supply we are using can be adjusted by removing the potentiometer that manually adjusts the voltage and hooking a digital to analog convertor up to the wiper arm. In this case, 2.5V out of the DAC corresponds to 30V out of the power supply. The issue that we ran into is that the reference on the power supply control circuit changes as we change the output voltage. Therefore we had to isolate the DAC and our microcontroller circuit from the power supply side of the circuit. We implemented optoisolators and a DC-DC convertor to achieve this. In this way the right and left sides of the circuit above are electrically isolated.

The next challenge with this circuit is to create a feedback loop to sense the voltage at the device under test. We do this because as the output current of our device under test(DUT) increases, the voltage drop across our current sensing resistors increases. This must be compensated for in order to keep the voltage constant at the DUT. This is accomplished by dividing the voltage at the DUT and dividing it down. We then send this voltage into an analog to digital convertor and the digital information is sent across the optoisolators to the isolated side of the circuit where it is then sent into a digital to analog convertor and then to the inverting terminal of an op-amp. Where, the non-inverting terminal is connected to the desired set-point. In this way the op-amp compensates for the voltage drop across the sense resistor, keep the voltage at the DUT constant.

<u>Microcontroller, ADC, and DACs Schematics</u>

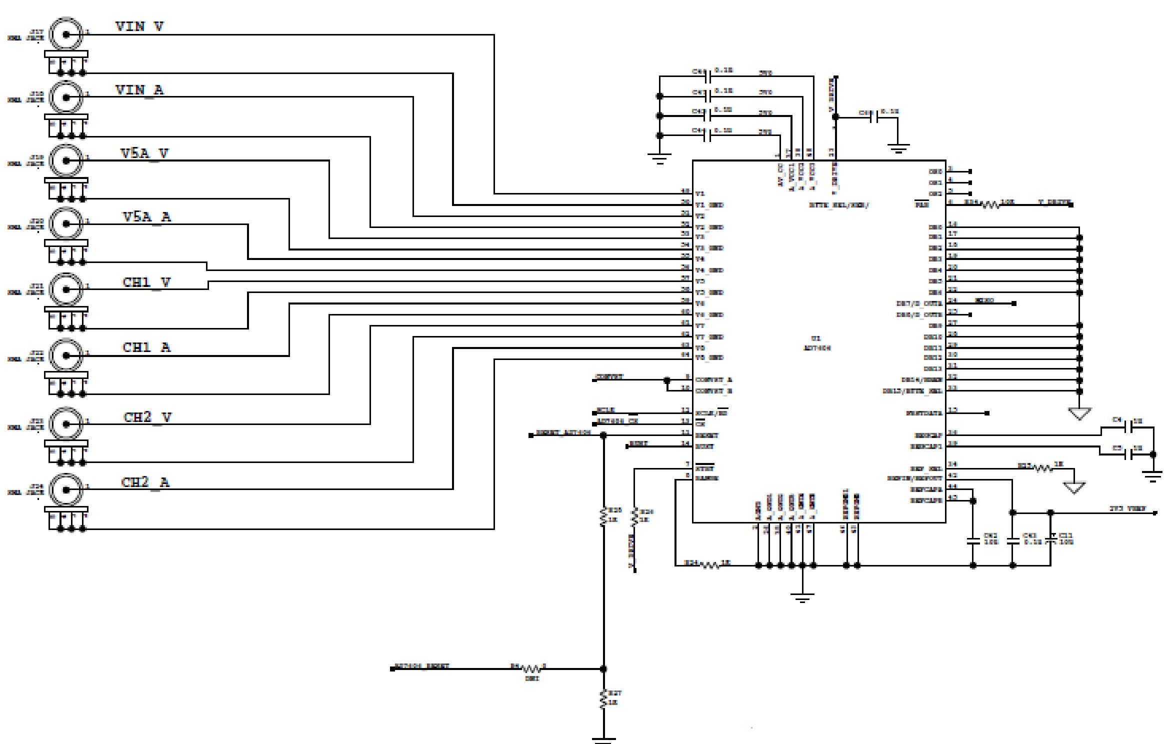


Figure 10: 16-Bit, 8Channel, Simultaneous Sampling ADC

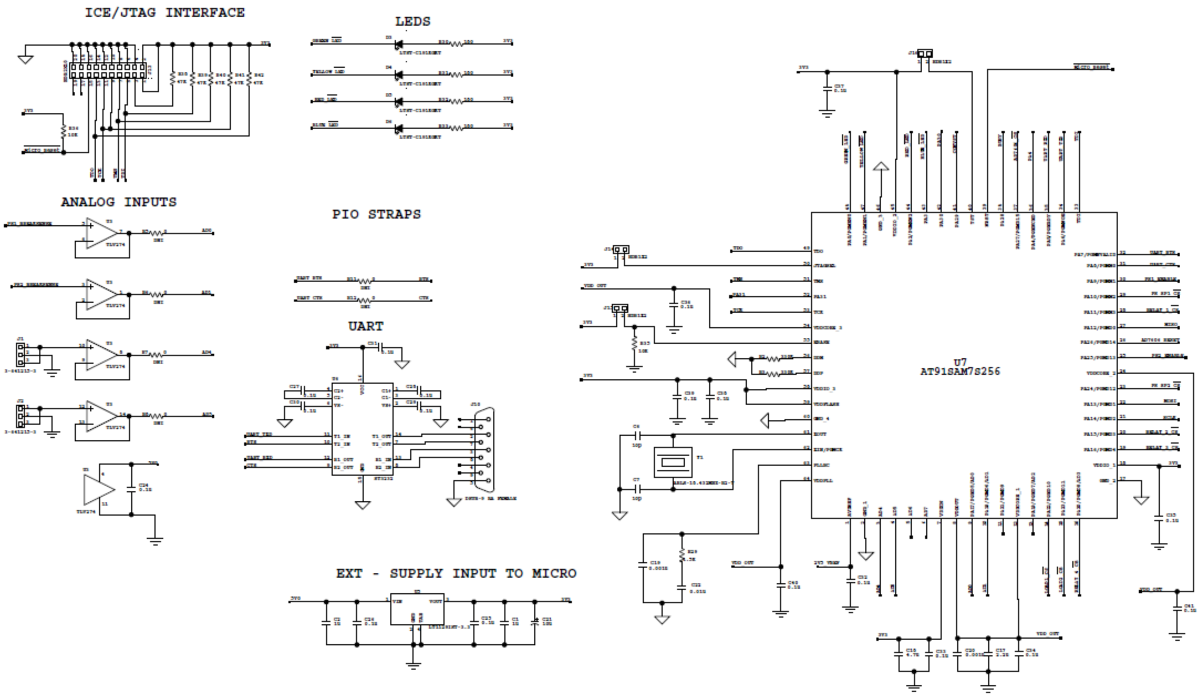


Figure 11: AT91SAM7S256 Microcontroller and Associated Circuitry

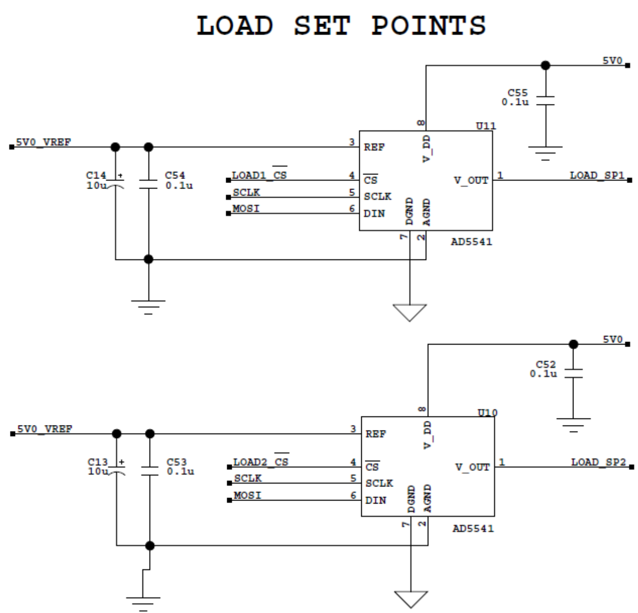


Figure 12: Load Set Point DACs

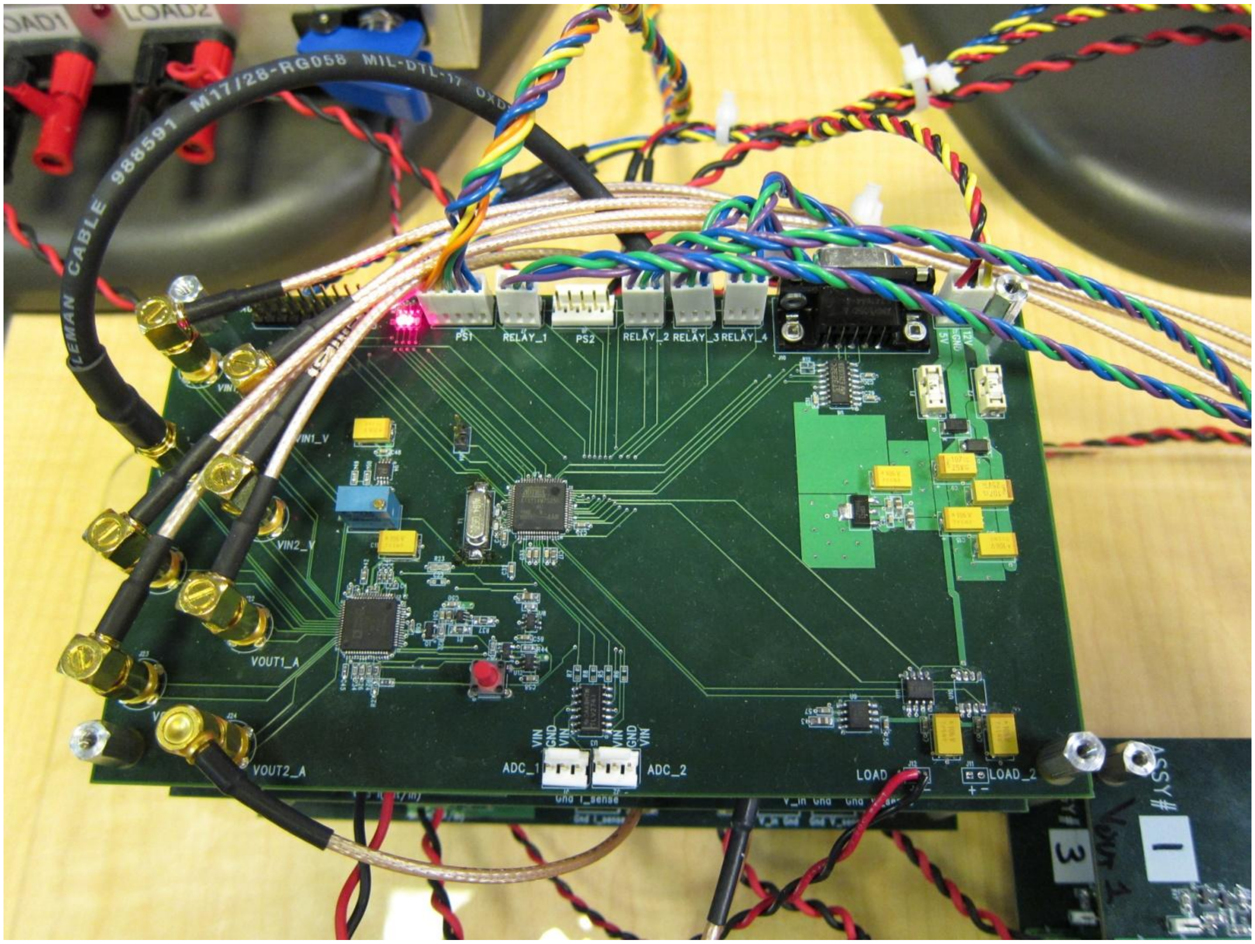


Figure 13: ADC, DAC, and Microcontroller Board

Theory of Operation

This is the last board that we designed for this project. It contains our microcontroller, load setpoint DACs, and the main ADC for taking our measurements. Our microcontroller controls the relay drivers on our measuring board, loads, power supplies, main ADC, as well as communicates with the computer.

Our ADC is the AD7606 which is a 16-Bit, 8-channel, simultaneous sampling ADC. This device allows two different input voltage ranges, +/- 10V and +/- 5V. We used the following the equations to determine the resolution of each range.

$$LSB = \frac{+F_s - (-F_s)}{2^{16}}$$

@ +/- 10V: Resolution = 305µV
@ +/- 5V: Resolution = 152µV

Because the +/- 5V range resolution is twice as good, we chose to go with this range.

To control the load we use DACs. We chose to use the AD5541 DAC for our project because of its ease of use. The loads that we are using are calibrated for a 1 to 1 correlation between voltage applied and current out. This means that if we apply 1V to the load set point it will draw 1A.

This board also allows the microcontroller to communicate with a computer via RS-232. To do this we have a UART chip on our board. All of the instructions from the computer come over this line. The ADC measurement readings are then sent back to the computer over this line where the numbers are processed and converted into power readings.

Software

Theory of operation

The software portion of the Automated Efficiency Meter project is to control the hardware by taking efficiency measurements, relay the data to a computer, and provide a programmable user interface. There are two parts to the software portion of the Automated Efficiency Meter, the user interface and the code loaded onto the SAM7S256 microprocessor. Each part will be explained individually.

SAM7S256:

The SAM7S256 is a microprocessor manufactured by the Atmel Corporation. This microprocessor performs the following functions:

1) **Read the 8-channel simultaneously sampling Analog to Digital Converter (ADC).**

The micro uses SPI (Serial Peripheral Interface) communication to take in readings from the ADC. SPI communication works using three or four lines which are data out, data in, a clock, and a chip select. In this case we only need three lines because we are not sending anything to the ADC we are just reading the samples. The following timing diagrams illustrates how the micro communicates with the ADC:

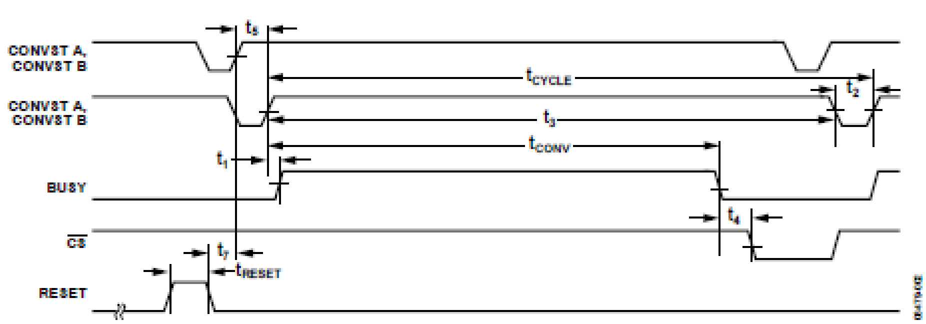


Figure 2. CONVST Timing—Reading After a Conversion

CONVSTA and CONVSTB stand for conversion start A and conversion start B. Each one of these signals starts a conversion process on 4 of the 8 channels on the ADC. If you tie these lines together then all 8 channels are sampled simultaneously. The BUSY signal comes from the ADC and indicates that the ADC is still in the conversion process.

The micro waits for BUSY to drop low before taking any readings. Once BUSY drops low the micro starts SPI communication with the ADC by setting CS low and then feeding the ADC a clock. The ADC sends eight sixteen bit numbers to the micro which are latched in on the rising edge of the clock. The following diagram gives an illustration of how the reading process executes:

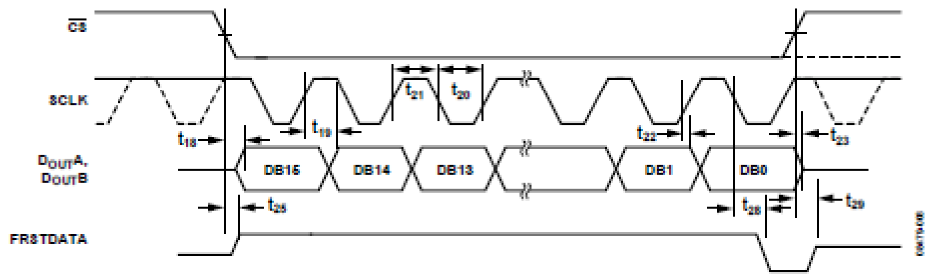


Figure 6. Serial Read Operation (Channel 1)

2) Control the load and power supply

Packet Digital has built a programmable load that we are using for the project. We used a 16 bit DAC to control the load and communicate to it via SPI. Also, to communicate with the programmable power supply the same 16 bit DAC was used. A flowchart for the micro is illustrated in the following diagram:

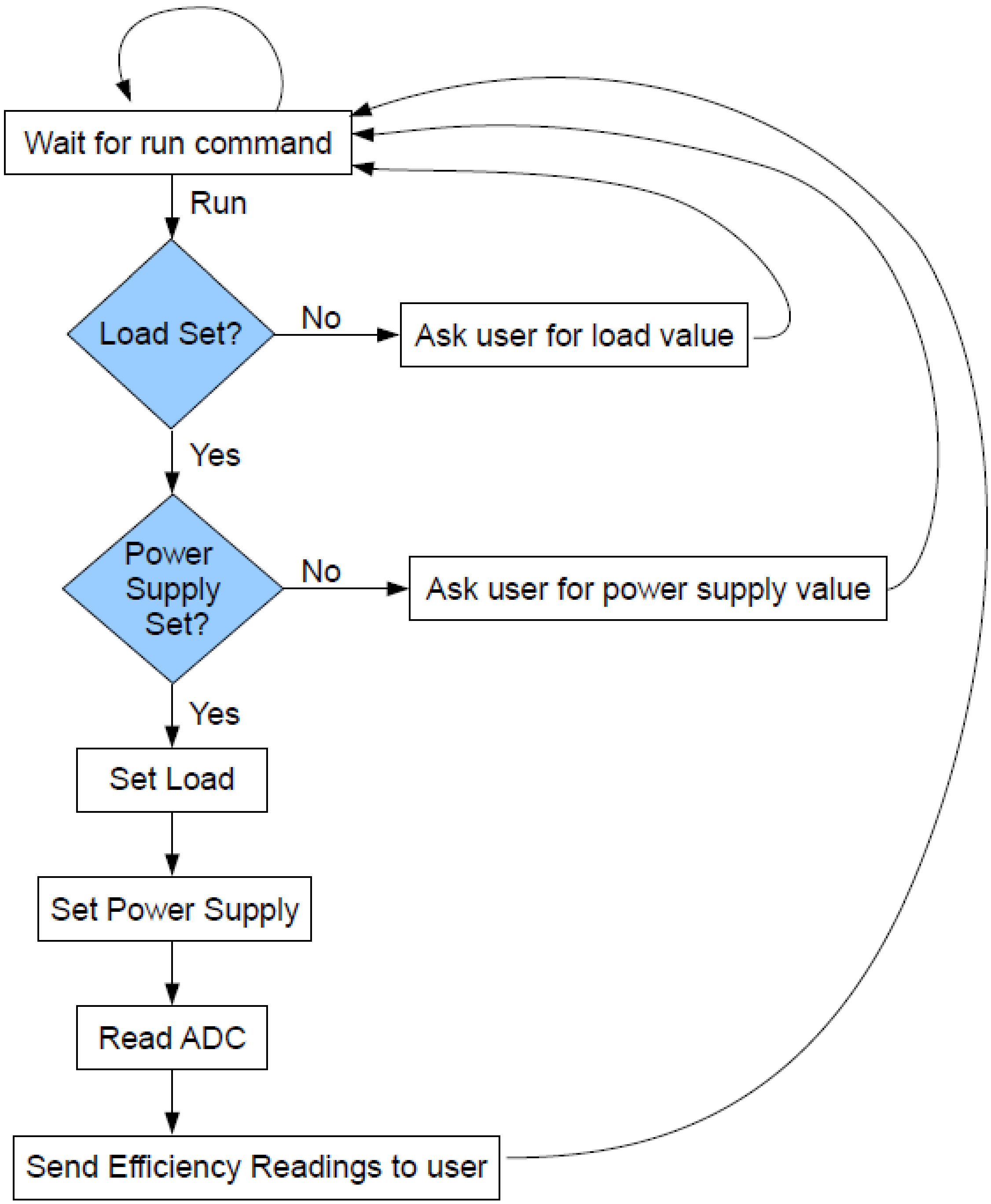


Figure 14: Software Flowchart

User Interface:

The user interface we incorporated into the project is a Python GUI. Python is a programming language and is very useful for serial port communication with a microprocessor. By running a

python script you can eliminate errors and allow the user to work more efficiently. Here is a screen capture of the GUI:

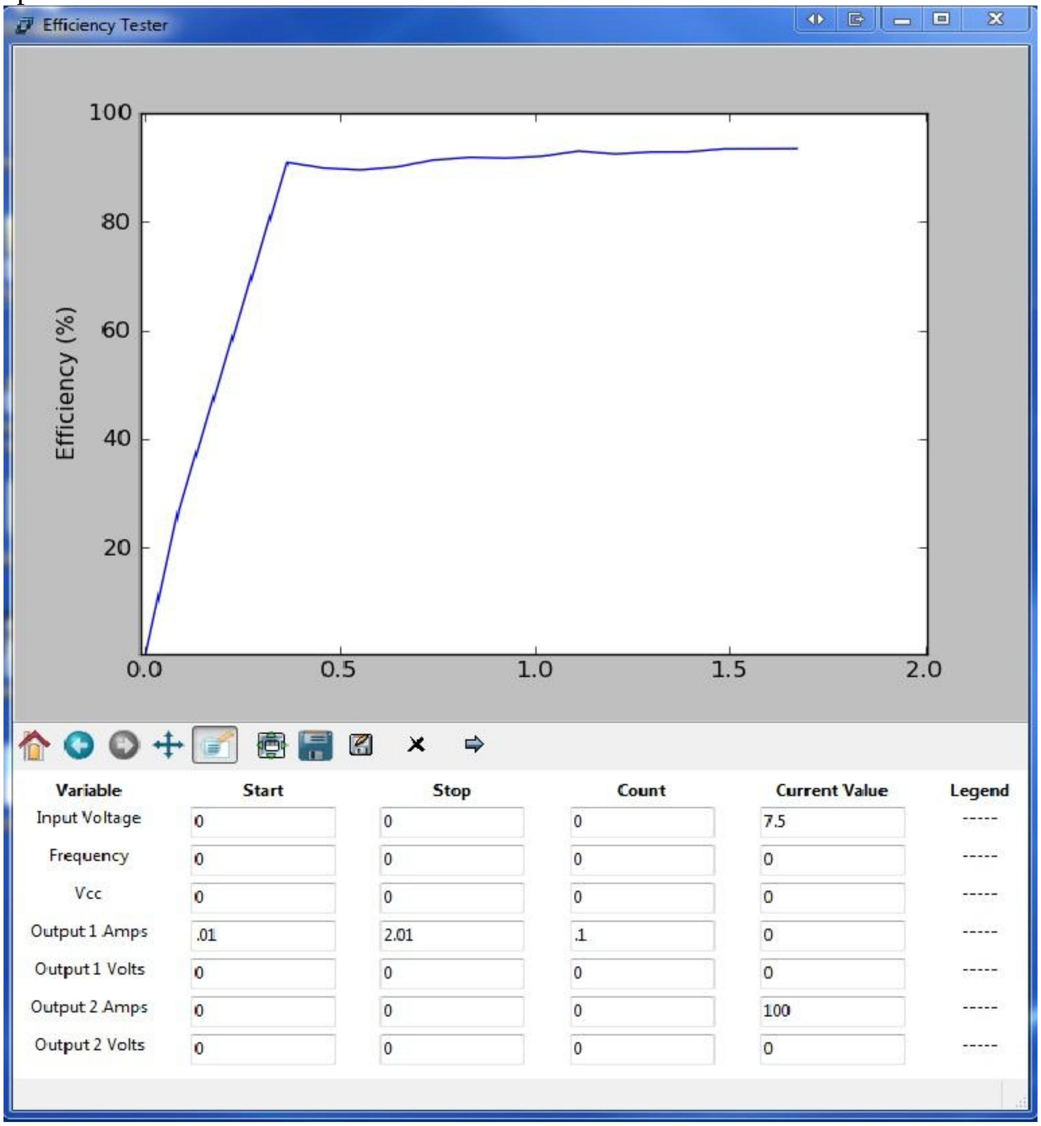


Figure 15: User Interface

To run an efficiency test the user simply needs to put in the start and stop currents and how many tests they wish take and then click run. Python will then communicate with the micro and run the efficiency tests. Once the required tests have been taken the micro feeds the results back to Python and plots the efficiency versus current curve for the user. The results are also saved into a csv file.

Troubleshooting

Before troubleshooting always disconnect power. If smoke comes out of part, replace part.

Comments

We have learned an overwhelming amount while doing this project. We designed three circuit boards from scratch. We had to make a voltage regular, 4 DACs, an ADC, microcontroller, programmable loads, and a programmable 4-terminal power supply all work together. Every possible thing that could go wrong did go wrong. We had heating issues with the sense resistors. We also experienced ESD issues with the power measuring boards. We had a lot of trouble getting our ADC working. We finally had to design our own board in order to get the ADC to work. We also had to learn python which neither of us have ever used before. We learned how to use a microcontroller that none of us have either used before. We also ran into innumerable problems with our software tools and the code that we wrote. In the end we did get our project work and it met all of our requirements which was an amazing accomplishment.

Costs

ITEM	QTY	PART NUMBER	DESCRIPTION	PRICE	TOTAL	Purchased From
1	40	490-1512-1-ND	CAP CER 10000PF 50V 10% X7R 0603	0.0170	0.680	Digikey
2	10	PCC2151CT-ND	CAP CERAMIC 1000PF 50V NP0 0603	0.0870	0.870	Digikey
3	8	399-5175-1-ND	CAP TANT 100UF 25V 10% SMD	2.9600	23.680	Digikey
4	10	478-1775-1-ND	CAP TANT LOWESR 35V 10UF 10% SMD	1.5010	15.010	Digikey
5	40	587-2400-1-ND	CAP CER 1.0UF 50V X5R 10% 0603	0.2250	9.000	Digikey
6	36	A31112-ND	CONN HEADER VERT 2POS .100 TIN	0.1152	4.147	Digikey
7	4	A30787-ND	CONN HEADER VERT 3POS .100 30AU	0.7700	3.080	Digikey
8	4	A30790-ND	CONN HEADER VERT 6POS .100 30AU	1.5400	6.160	Digikey
9	8	J840-ND	CONN RECEPT STR JACK PCB .155"	4.5900	36.720	Digikey
10	20	A98342-ND	TERM BLOCK 2POS SIDE ENT 5.08MM	0.4980	9.960	Digikey
11	16	ES2BA-FDICT-ND	DIODE SUPER FAST SMD 100V 2A SMA	0.4560	7.296	Digikey
12	4	F1223CT-ND	FUSEBLOCK W/1.5A FUSE SMD FAST	2.7000	10.800	Digikey
13	6	AD8221BR-ND	IC AMP INST PREC LN 18MA 8SOIC	9.3000	55.800	Digikey
14	32	BSS138CT-ND	MOSFET N-CH 50V 220MA SOT-23	0.4280	13.696	Digikey
15	16	Z954-ND	RELAY PC MNT 20A SPST 12VDC	7.4800	119.680	Digikey
16	4	RMCF2512ZT0R00CT-ND	RES 0.0 OHM 1W 2512 SMD	0.4400	1.760	Digikey
17	4	D2TO-.100A-ND	RESISTOR .100 OHM 35W SMD DPAK	12.4400	49.760	Digikey
18	4	P10.2AACT-ND	RES 10.2 OHM 1/2W 1% 1210 SMD	0.5200	2.080	Digikey
19	8	P11.5KHCT-ND	RES 11.5K OHM 1/10W 1% 0603 SMD	0.0400	0.320	Digikey
20	15	P200GCT-ND	RES 200 OHM 1/10W 5% 0603 SMD	0.0300	0.450	Digikey
21	10	P4.02KCCT-ND	RES 4.02K OHM 1/8W 1% 0805 SMD	0.0700	0.700	Digikey
22	10	P49.9CCT-ND	RES 49.9 OHM 1/8W 1% 0805 SMD	0.0700	0.700	Digikey
23	5	P56.0KHCT-ND	RES 56.0K OHM 1/10W 1% 0603 SMD	0.0400	0.200	Digikey
24	4	P931KCCT-ND	RES 931K OHM 1/8W 1% 0805 SMD	0.0700	0.280	Digikey
25	6	490-2971-ND	TRIM POT CERM 100KOHM 12TRN TOP	1.3800	8.280	Digikey
26	4	490-2874-ND	TRIM POT CERM 1KOHM 25TRN TOP	0.9200	3.680	Digikey
27	4	490-2882-ND	TRIM POT CERM 200KOHM 25TRN TOP	0.9200	3.680	Digikey

28	8	490-2880-ND	TRIM POT CERM 2KOHM 25TRN TOP	0.9200	7.360	Digikey
29	4	490-2883-ND	TRIM POT CERM 2MOHM 25TRN TOP	0.9200	3.680	Digikey
30	4	AD588JQ-ND	IC PREC VOLT REF PROG 16-CDIP	23.0400	92.160	Digikey
31	4	HS406-ND	TOP MOUNT HEATSINK .45" D2PAK	1.9500	7.800	Digikey
32	10	PCC2277CT-ND	CAP .1UF 25V CERAMIC X7R 0603	0.04	0.420	Digikey
33	30	311-1369-1-ND	CAP CERAMIC .1UF 16V Y5V 0603	0.02	0.450	Digikey
34	10	490-1570-1-ND	CAP CER 1000PF 25V Y5V 0603	0.05	0.450	Digikey
35	10	445-3465-1-ND	CAP CER 10UF 10V Y5V 1206	0.18	1.760	Digikey
36	2	495-1578-1-ND	CAP TANT 10UF 35V 10% LOESR SMD	2.21	4.420	Digikey
37	15	587-1437-1-ND	CAP CER 1.0UF 35V X5R 0603	0.23	3.375	Digikey
38	1	A30797-ND	CONN HEADER RT/A 5POS .100 30AU	1.71	1.710	Digikey
39	1	A30788-ND	CONN HEADER VERT 4POS .100 30AU	0.99	0.990	Digikey
40	1	102-1345-ND	CONVERTER DC/DC +/-5V OUT 1W	4.22	4.220	Digikey
41	4	497-7081-1-ND	IC HEX SCHMITT INVERTER 14-SOIC	0.53	2.120	Digikey
42	2	OP184FSZ-ND	IC OPAMP GP R-R 4.25MHZ LN 8SOIC	3.60	7.200	Digikey
43	1	751-1288-1-ND	OPTOCOUPLER PHOTOTRNS 100% 8SOIC	0.97	0.970	Digikey
44	1	LTC1799CS5#TRMPBFCT-ND	IC OSC SILICON 33MHZ TSOT23-5	3.89	3.890	Digikey
45	1	BSS138CT-ND	MOSFET N-CH 50V 220MA SOT-23	0.63	0.630	Digikey
46	4	160-1371-5-ND	OPTOISOLATOR 4CH SMD	1.02	4.080	Digikey
47	5	P0.0GCT-ND	RES 0.0 OHM 1/10W 0603 SMD	0.03	0.150	Digikey
48	5	P10KGCT-ND	RES 10K OHM 1/10W 5% 0603 SMD	0.03	0.150	Digikey
49	1	P110KHCT-ND	RES 110K OHM 1/10W 1% 0603 SMD	0.04	0.040	Digikey
50	1	P1.00MHCT-ND	RES 1.00M OHM 1/10W 1% 0603 SMD	0.04	0.040	Digikey
51	1	P20.0CCT-ND	RES 20.0 OHM 1/8W 1% 0805 SMD	0.07	0.070	Digikey
52	1	P2.0KDBCT-ND	RES 2.0K OHM 1/10W .1% 0603 SMD	0.54	0.540	Digikey
53	1	P49.9HCT-ND	RES 49.9 OHM 1/10W 1% 0603 SMD	0.04	0.040	Digikey
54	20	P499HCT-ND	RES 499 OHM 1/10W 1% 0603 SMD	0.04	0.800	Digikey
55	22	P698HCT-ND	RES 698 OHM 1/10W 1% 0603 SMD	0.04	0.880	Digikey
56	1	P787HCT-ND	RES 787 OHM 1/10W 1% 0603 SMD	0.04	0.040	Digikey
57	1	P88.7KHCT-ND	RES 88.7K OHM 1/10W 1% 0603 SMD	0.04	0.040	Digikey
58	1	490-2888-ND	TRIM POT CERM 5KOHM 25TRN TOP	0.92	0.920	Digikey
59	1	ADR421ARMZ-ND	IC VREF PREC 2.5V 10MA 8-MSOP	5.56	5.560	Digikey
60	30	311-1369-1-ND	CAP CERAMIC .1UF 16V Y5V 0603	0.02	0.450	Digikey
61	20	490-1575-1-ND	CAP CER .1UF 25V Y5V 0603	0.02	0.360	Digikey
62	1	PCC1750CT-ND	CAP 10000PF 16V CERM X7R 0603	0.17	0.170	Digikey
63	2	399-5697-1-ND	CAP CER 1000PF 50V X8R 0603	0.24	0.480	Digikey
64	2	PCC1941CT-ND	CAP CERAMIC 10PF 100V NP0 0603	0.21	0.420	Digikey
65	6	478-1775-1-ND	CAP TANT LOWESR 35V 10UF 10% SMD	1.73	10.380	Digikey
66	1	495-1578-1-ND	CAP TANT 10UF 35V 10% LOESR SMD	2.21	2.210	Digikey
67	1	587-1782-1-ND	CAP CER 4.7UF 25V X5R 0805	0.42	0.420	Digikey
68	2	A32116-ND	CONN D-SUB RCPT R/A 9POS GOLD	3.02	6.040	Digikey
69	1	MHD20K-ND	SHROUDED HEADER 20 POS RT ANGLE	2.54	2.540	Digikey
70	4	A30787-ND	CONN HEADER VERT 3POS .100 30AU	0.77	3.080	Digikey
71	1	LT1129IST-3.3#PBF-ND	IC LDO REG W/SD 3.3V SOT223-3	5.00	5.000	Digikey
72	2	497-3731-1-ND	C TXRX 3-5.5V RS232 LP 16-SOIC	2.33	4.660	Digikey
73	4	160-1446-1-ND	LED GREEN CLEAR THIN 0603 SMD	0.53	2.120	Digikey
74	1	AT91SAM7S256C-AU-ND	IC ARM7 MCU 32BIT 256K 64LQFP	12.47	12.470	Digikey

75	1	296-11981-1-ND	IC OPAMP GP R-R 3MHZ QUAD 14SOIC	1.55	1.550	Digikey
76	2	EG4350CT-ND	SWITCH TACT SEAL 4.7MM SMT 160GF	1.20	2.400	Digikey
77	1	ADR421ARMZ-ND	IC VREF PREC 2.5V 10MA 8-MSOP	5.56	5.560	Digikey
78	1	MAX6250ACSA+-ND	IC V-REF PREC 5V LN 8-SOIC	8.86	8.860	Digikey
79	1	535-9072-1-ND	CRYSTAL 18.432MHZ 18PF SMD	0.56	0.560	Digikey
80	1	Pettibone-150-A	PCB – Sensing board – Rev.1	66.0000	66.000	Advanced-PCB
81	4	Pettibone-150-B	PCB – Sensing board – Rev.2	66.0000	264.000	Advanced-PCB
82	1	Lab-020-A	PCB – Power Supply Mod – Rev.1	66.0000	66.000	Advanced-PCB
83	1	Lab-040-A	PCB – DAC, ADC, Microcontroller – Rev.1	66.0000	66.000	Advanced-PCB
84	1	DEV-00775	Header Board Atmel SAM7-256	45.9500	45.950	Sparkfun
85	1	EVAL-AD7606EDZ	AD7606 Evaluation Board	150.000 0	150.000	Analog Devices
			TOTAL		1273.104	